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Analysis of daylight calculated using the EnergyPlus programme

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ABSTRACT

In order to properly evaluate the thermal energy performance of buildings it is also necessary to analyse the use of daylight, since this influences the thermal load of a building. In this context, the aim of this study was to evaluate the calculation of internal illuminances carried out using the EnergyPlus simulation programme. The analysis was carried out through a comparison of the Useful Daylight Illuminances (UDI) and the daylight factor (DF) estimated using the EnergyPlus programme with the results from another two programmes: Daysim/Radiance and TropLux. Also, the external horizontal illuminance estimated using EnergyPlus was compared with that measured in Florianópolis, Santa Catarina State, Brazil, between 2003 and 2005. The simulations were carried out for three different rooms: one square (5 m × 5 m × 3 m), one shallow rectangular (10 m × 5 m × 3 m) and one deep rectangular (5 m × 10 m × 3 m). From this analysis it was verified that the EnergyPlus programme has a problem related to both the DF and the external illuminance values. A comparison between the DF values calculated using the three programmes shows that there is a problem in EnergyPlus related to solving the internal reflection, such that the greater the importance of the portion of light reflected, the greater the difference found between the programmes. A comparison between the calculated and measured external horizontal illuminances shows differences greater than 100% both for the diffuse and direct illuminances indicating that the EnergyPlus programme overestimates these values.

Contents

1. Introduction

Concerns regarding the abusive use of energy and with climate change caused by gas emissions have repercussions for civil construction and for investment in renewable energy sources. Population growth and economic development have led to an

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increase in the demand for energy which, according to Asif and Muneer [1], is mainly obtained from fossil fuels. According to these authors, fossil fuels represent 80% of the global demand for energy, while 13.5% comes from renewable energy and 6.5% from nuclear energy. Energy efficiency is another important factor related to the energy issue; according to Omer [2] a building has three parameters directly related to energy consumption: thermal comfort (thermal conditioning), visual comfort (lighting) and air quality (ventilation).

Daylight is an important strategy in obtaining a more efficient architecture which is integrated with the climate in which it is inserted, and therefore it is necessary to study the ambient light. In order to carry out a more advanced study there is a need for data related to the daylight of the location in which the building will be constructed. However, the analysis of the ambient daylight must also take into account the heat exchange which occurs through the windows.

Studies such as those by Ochoa and Capeluto [3], Li and Wong [4], and Ghisi and Tinker [5] use the joint simulation of the daylight and heat gain of a building in order to verify the performance of the design decisions taken [3], to study the daylight in dense areas [4] and to analyse the ideal window size in climatised buildings [5]. These analyses rely on the accuracy of the results obtained by the simulation programmes. In these studies EnergyPlus programmes were used by Ochoa and Capeluto [3] and Li and Wong [4], and the VisualDoe programme by Ghisi and Tinker [5].

The EnergyPlus simulation programme, among other programmes, allows the joint analysis of the heat exchanges and daylight gain through the window, where the calculation of daylight is carried out through the DF and the external illuminance. The external illuminance is calculated through a model developed by Perez et al. [6]. According to Winkelmann and Selkowitz [7], the validation of illumination carried out by the EnergyPlus programme is the same as that of DOE-2, since the EnergyPlus algorithm was based on the latter. The validation was partly carried out through a comparison between the results of DOE-2, Superlite and the artificial sky measurements of LBL (Lawrence Berkeley Laboratory). These comparisons verified an average difference of 15% among the three methods, with the exception of the areas very close to or far from the window, where a greater difference was verified. This difference is not mentioned by the authors.

The study by Loutzenhiser et al. [8] shows a comparison between the results of simulations carried out using the EnergyPlus and DOE-2 programmes, with a real model, for the climate of Ankeny, IA, USA (41°43′N, 93°36′W). A comparison of the illuminances was carried out for building models using different shading devices on the windows, such as Nysan roller shades, fixed slat angle horizontal mini-blinds and motorised mini-blinds. The windows are made of clear double glazing (two 6-mm clear glass sheets with 13.2 mm airspace), for rooms with south, east and west facing façades. According to the authors, none of the programmes gave results with 95% confidence for the reference points. For the models in which the simulation was carried out using the two programmes, the results obtained for EnergyPlus and DOE-2 were different. For the room with a west facing façade the difference between EnergyPlus and the real data was 76%, while between DOE-2 and the real data it was 53%.

Given the differences found between the illuminances resulting from the simulation carried out using the EnergyPlus programme, illustrated by the studies mentioned above, this paper aims to analyse the calculation method used by EnergyPlus. The analysis of this study was carried out for the climate of the city of Florianópolis, located in southern Brazil (27°35′48″S, 48°32′57″W).

2. Objective

This paper aims to evaluate the daylight calculation carried out by the EnergyPlus programme, through a comparison of the simulation results and the measured data for the city of Florianópolis in southern Brazil.

3. Simulation programmes

The use of simulation programmes facilitates the analysis of large quantities of data required for the calculation of the thermal energy and lighting performance of buildings. An analysis of the results of the computational simulations can be used to guide the decisions related to the building design. In this study three simulation programmes will be used: EnergyPlus, Daysim/Radiance and TropLux.

The EnergyPlus programme was created based on the combination of two programmes BLAST and DOE-2. This programme works with the heat balance of BLAST, with a generic model of conditioned air, new algorithms of heat transfer and heat flux of air between zones [9], while the daylight programme originates from DOE-2 [10].

The programme allows the definition of two points of reference, from which the internal illuminance calculations will be carried out. From these two points two DF values will be calculated, one for the contribution of light from the sky vault and the other for direct sunlight. This process is carried out for each of the points and for each window of the room. In order to calculate the illumination at other points of the room, weighting between the results of these two initial reference points is carried out.

The calculation of internal illuminance is carried out through the integration between the DF relating to the sky vault portion and the DF of the sunlight, multiplied by their corresponding external illuminance. For the calculation of the diffuse illumination portion, the weighting of the DF between two types of sky is carried out. The calculation of external horizontal illuminance is performed using the model of Perez et al. [6].

The Daysim/Radiance programme was developed by the National Research Council Canada (NRCC) and the Fraunhofer Institute for Solar Energy Systems in Germany, in order to calculate the illuminances for a period of 1 year, in a fast way regardless of the type of sky [11]. This programme simulates the daylight through the daylight coefficient, based on the Radiance programme, which uses the method of ray tracing, and the sky model developed by Perez et al. [6], to allow the simulation of the illuminances under any sky condition [12]. The simulation is carried out using a tridimensional model of the environment to be analysed. In the model, the optical properties of the surfaces and of the weather file are defined, from which data such as the latitude, longitude and solar radiation are taken.

The Brazilian programme TropLux was developed to satisfactorily attend the need to obtain the daylight of the tropics, which is not the case in most programmes available [13]. The programme is based on three fundamental concepts: the Monte Carlo method, the ray tracing method and the concept of daylight coefficients. The Monte Carlo method offers a statistical approach to solve the multiple integrals. The ray tracing technique follows the path of a ray between surfaces, its main advantage being the possibility to offer simple theoretical solutions for complex geometries. The daylight coefficients relate the illuminance of a certain surface, from a given subdivision of the sky, to the normal illuminance of an unobstructed plane, from the same subdivision. For this calculation, TropLux adopts two types of subdivision of the sky: for the calculation of the reflected component the subdivision proposed by the CIE (*Commission Internationale de l'Eclairage*) is used, into 145 parts; and for the calculation of the direct component a

subdivision into 5221 parts is used, in order to obtain a better precision of the results according to the solar altitude [13]. In order to carry out the simulation of the daylight distribution of an environment, further input data are required such as the geometry of the room, planes, windows and the characteristics of the materials, along with the geographical location. The programme also allows the processing of surfaces which are diffuse, specular and mixed, as well as opaque, transparent and translucid.

The choice of these three programmes is based on the relation between them: both the EnergyPlus and the Daysim/Radiance programmes estimate the external illuminance using the sky model developed by Perez et al. [6]. This model bases the calculation of the external illuminance on data such as radiation, solar zenith angle and atmospheric water content, showing the variation in the daylight. The Daysim/Radiance and TropLux programmes use the same calculation method, the daylight coefficient. This process facilitates an evaluation of the calculation of illuminance carried out in EnergyPlus.

4. Methodology

This study was carried out in two stages. The first is based on a comparison of the results of the three above-mentioned programmes. In the second stage, the internal illuminance measured in Florianópolis was compared with the value calculated using the model of Perez et al. [6].

The simulations were carried out for models with three different dimensions: a square room, in the proportion of 1:1 (5 m × 5 m × 3 m); a shallow rectangular room, in the proportion of 2:1 (10 m × 5 m × 3 m); and a deep rectangular room, in the proportion of 1:2 (5 m × 10 m × 3 m), as represented in Fig. 1. These models have a window to wall ratio (WWR) of 50%, with the window in a south facing façade in order to reduce the entrance of direct light in the environment. In the windows the use of 3 mm clear glass with a visible transmittance of 0.88 was considered. The models have white walls and ceilings, with a reflectance of 0.85, and a beige floor, with a reflectance of 0.60. In all of the simulations the work surface was considered to be at a height of 0.75 m.

The simulations of the internal illuminances were carried out based on the weather data of Florianópolis for the year 2005, while for the external horizontal illuminance the data for 2003–2005 were used. The data used in the weather files were collected by LabSolar (Laboratory of Solar Energy), while the illuminances, used for the simulations in the TropLux programme, were collected by EMIN-Floripa (Daylight Measurement Station of Florianópolis), through LabSolar and LabCon (Laboratory of Environmental Comfort), both based at the Federal University of Santa Catarina State (UFSC) in Florianópolis. The data collected were used on an hour basis.

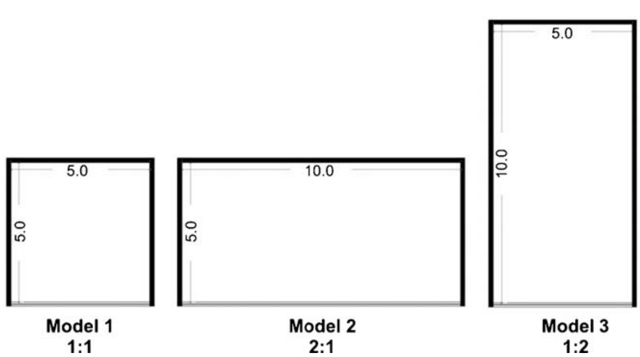

Fig. 1. Dimensions of the models studied.

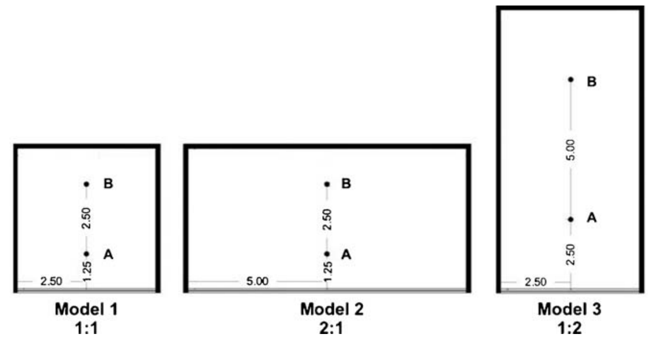

Fig. 2. Locations of the points analysed for the calculation of illuminance as a function of the geometry.

4.1. Analysis of internal illuminances

The average hourly values of the illuminances were compared in order to verify the difference between the illuminances calculated by the three programmes according to the hour of the day. Although the Daysim/Radiance and TropLux programmes allow the simulation of several reference points, the EnergyPlus programme carries out the complete calculation of only two reference points for each area of simulation. For rooms with more reference points the illuminance of these points is the result of the weighting of the two initial reference points.

In order to verify the influence of the geometry of the room on the internal illuminances found, three room dimensions were simulated as shown in Fig. 1. The reference points (A and B) analysed in these simulations are represented in Fig. 2.

4.2. Analysis of the daylight distribution

In order to compare the programme responses for the distribution of daylight across the room, the Useful Daylight Illuminances (UDI) scheme was used, which allows the verification of the frequency of occurrence of predetermined illuminance ranges. For this analysis the simulation was carried out for a period of 1 year, during work hours (between 08:00 and 18:00) using the model with the proportion of 1:1 (model 1 in Fig. 1). As mentioned above, Daysim/Radiance and TropLux allow the simulation of several points in the room, while in EnergyPlus only two points are possible. Thus, in this analysis the map of illuminances generated by EnergyPlus was used, resulting from the interpolation of the illuminances of the two reference points.

From the illuminance values for the period of 1 year, during work hours, the frequencies with which each illuminance range occurred was determined. The pre-established ranges used were the same as those determined by Nabil and Mardaljevic [14]:

a. UDI Fell-short, comprising illuminances between 100 and 500 lx, where the artificial light is used only to complement the natural light.
b. UDI Achieved, comprising illuminances between 500 and 2000 lx, where the natural light totally replaced the artificial light without causing discomfort.
c. UDI Exceeded, for illuminances above 2000 lx, which are considered excessive and may cause visual and/or thermal discomfort.

Based on the separation of these illuminance ranges it will be possible to evaluate the distribution of illumination in the environment according to each simulation programme.

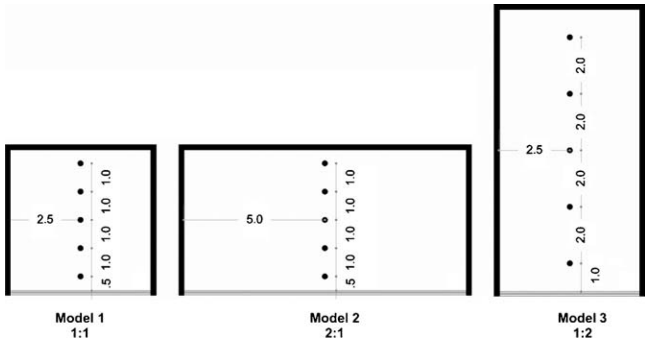

Fig. 3. Location of the points in the rooms for analysis of the daylight factor (DF).

4.3. Verification of the DF calculation

Since the internal illumination calculation in the EnergyPlus programme is carried out based on the DF, the values obtained for this index were compared with those of the other two programmes.

The simulations were carried out for three models: for each of them the DF was calculated for five points in the room, aligned with the centre of the window, at a height of 0.75 m, as shown in Fig. 3. As previously mentioned, the EnergyPlus programme carries out the complete calculation of illuminance for only two reference points, and weights these values for the other points required. This analysis was carried out for five points, in order to allow the analysis of the programme response with increasing distance between the points analysed and the window.

The Daysim/Radiance and TropLux programmes provided the DF as a simulation result and for the EnergyPlus programme it was calculated for a day with an overcast sky. The overcast sky day will be determined from the sky clearness index, according to the model of Perez et al. [6].

The daylight factor (DF) is determined through the relation between the illuminance of the point of reference, E_p, and the external horizontal illuminance, E_{hext}, according to Eq. (1), for overcast sky conditions.

$$\mathrm{DF} = \frac{E_p}{E_{hext}} \times 100\% \tag{1}$$

where DF is the daylight factor (%), E_p is the illuminance of the point of reference (lx) and E_{hext} is the external horizontal illuminance (lx).

4.4. Evaluation of the model developed by Perez

In this stage the external horizontal diffuse illuminances collected by EMIN-Floripa (Daylight Measurement Station of Florianópolis) were compared with those used by the EnergyPlus programme to calculate the internal illuminance. The external illuminance calculated by EnergyPlus was obtained through the method developed by Perez et al. [6]. Thus, for this comparison data on solar radiation, temperature, solar zenith angle and humidity measured in Florianópolis, between 2003 and 2005 by the measuring station of LabSolar and the illuminances measured by EMIN-Floripa will be used.

The model of Perez et al. [6] is based on four parameters to characterise the sky and estimate the illuminance, these being: sky clearness index (ε), solar zenith angle (Z), sky brightness index (Δ) and atmospheric water content (W). These parameters will be calculated based on the measured data for Florianopolis using the following equations. The sky clearness index (ε) is calculated through Eq. (2).

$$\varepsilon = \frac{[(I_{Dh} + I)/I_{Dh} + kZ^3]}{(1 + kZ^3)} \tag{2}$$

where ε is the sky clearness index (adimensional); I_{Dh} is the horizontal diffuse radiation (W/m^2); I is normal direct radiation (W/m^2); k is constant and equal to 1.041 and Z is the solar zenith angle in radians.

The sky brightness index (Δ) is determined using Eq. (3).

$$\Delta = \frac{I_{Dh} \times m}{I_0} \tag{3}$$

where Δ is the sky brightness index (adimensional); m is the relative optical air mass, and can be determined by: $m = 1/sen\gamma_s$, with γ_s being the solar altitude [rad]; and I_0 is the extraterrestrial radiation (W/m^2).

The atmospheric water content (W) is calculated through Eq. (4).

$$W = \exp(0.07 \times Td - 0.075) \tag{4}$$

where W is the atmospheric water content (cm); and T_d is the dew temperature (°C).

The diffuse horizontal illuminance was calculated through Eq. (5), and the direct illuminance through Eq. (6). In these equations different coefficients are used, according to the sky clearness categories given in Table 1.

$$E_{hDif} = I_{Dh}[a_i + b_i W + c_i \cos(Z) + d_i\, Ln(\Delta)] \tag{5}$$

$$E_{hDir} = \max\{0, I[a_i + b_i W + c_i \exp(5.73Z - 5) + d_i \Delta]\} \tag{6}$$

where E_{hDif} is the diffuse horizontal illuminance (lx); E_{hDir} is the direct horizontal illuminance (lx); I_{Dh} is the diffuse horizontal radiation (W/m^2); I is the direct horizontal radiation (W/m^2); W is the atmospheric water content (cm); Z is the solar zenith angle (rad); Δ is the sky brightness index (adimensional); and a_i, b_i, c_i, d_i are the coefficients, used according to the sky clearness (ε).

Table 1
Coefficients to calculate the external illuminances.

ε	Diffuse horizontal illuminance				Direct horizontal illuminance			
	a_i	b_i	c_i	d_i	a_i	b_i	c_i	d_i
1	97.24	−0.46	12.00	−8.91	57.20	−4.55	−2.98	117.12
2	107.22	1.15	0.59	−3.95	98.99	−3.46	−1.21	12.38
3	104.97	2.96	−5.53	−8.77	109.83	−4.90	−1.71	−8.81
4	102.39	5.59	−13.95	−13.90	110.34	−5.84	−1.99	−4.56
5	100.71	5.94	−22.75	−23.74	106.36	−3.97	−1.75	−6.16
6	106.42	3.83	−36.15	−28.83	107.19	−1.25	−1.51	−26.73
7	141.88	1.90	−53.24	−14.03	105.75	0.77	−1.26	−34.44
8	152.23	0.35	−45.27	−7.98	101.18	1.58	−1.10	−8.29

Source: Adapted from Perez et al. [6].

The correlations between the illuminances measured in Florianópolis were compared with those calculated using the model proposed by Perez et al. [6]. Furthermore, for a better evaluation of this model the following indices were used: mean bias deviation (MBD) and root mean square deviation (RMSD), calculated using Eqs. (7) and (8), respectively.

$$\mathrm{MBD} = \frac{\sum_i^N (y_i - x_i)/x_i}{N} \tag{7}$$

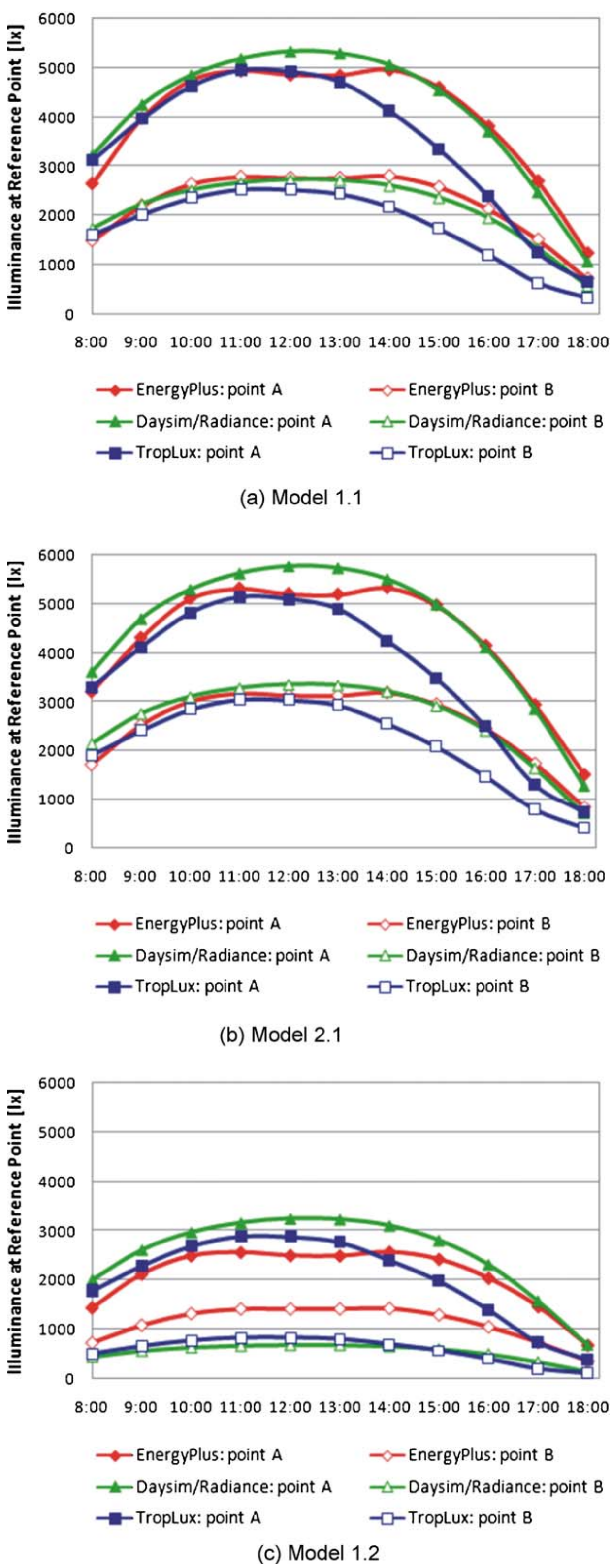

Fig. 4. Average values of the internal illuminances for a WWR of 50%.

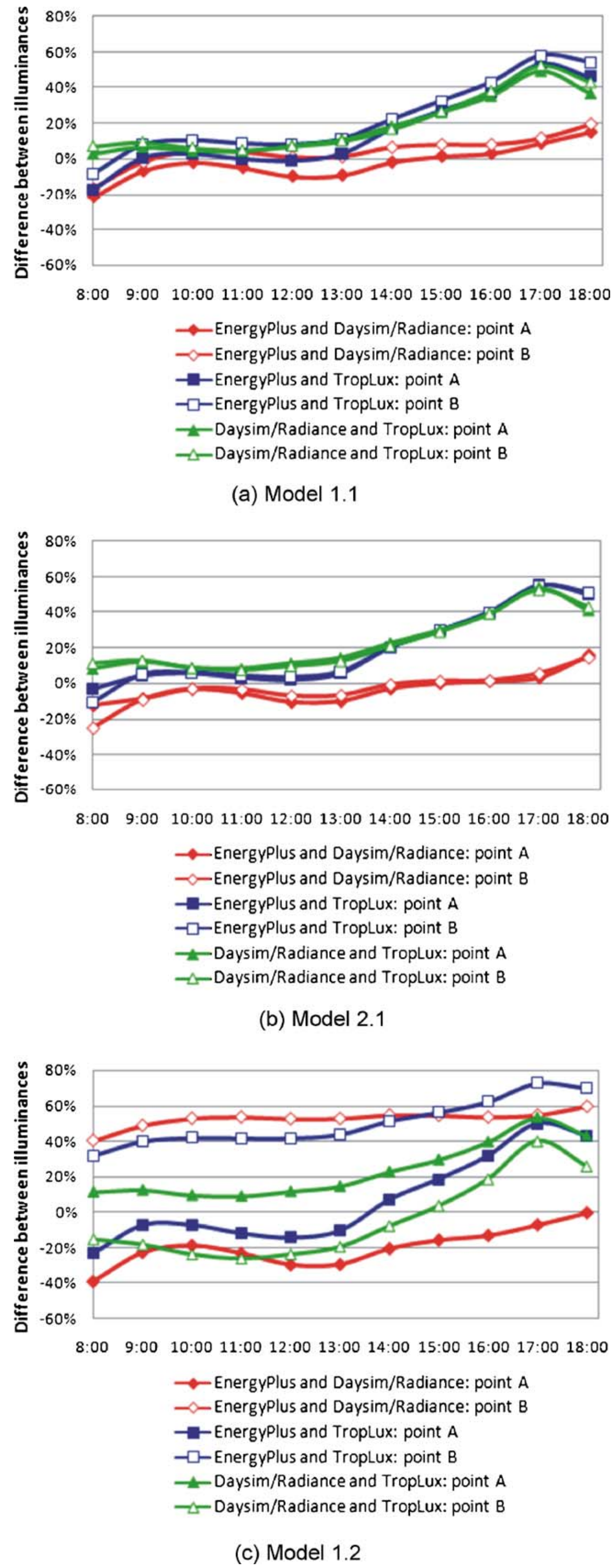

Fig. 5. Difference between the illuminances obtained using the three programmes.

$$\mathrm{RMSD} = \sqrt{\frac{\sum_i^N ((y_i - x_i)/x_i)^2}{N}} \quad (8)$$

where MBD is the mean bias deviation (%); RMSD is the root mean square deviation (%); y_i is the estimated illuminance (lx), x_i is the measured illuminance (lx) and N is the number of values analysed.

From the mean bias deviation it was possible to verify the tendency of the model to overestimate or underestimate the illuminances calculated, while the root mean square deviation showed the absolute error between the two sets of data analysed.

5. Results and discussion

The comparisons between the results of the simulations of the EnergyPlus, Daysim/Radiance and TropLux programmes are presented below. The results refer to the average internal illuminances, distribution of light in the internal environment for the period of 1 year, daylight factor of each environment analysed and the comparison between the external illuminances, for the city of Florianópolis.

5.1. Evaluation of the internal daylight

The illuminances were analysed, firstly, as a function of the hour. This comparison was carried out based on the average illuminances resulting from the simulations for the two reference points.

Fig. 4 shows the internal illuminances obtained by the three programmes, for the three room models while Fig. 5 shows the differences found between the programmes. In Fig. 4(a) it can be observed that there is a great similarity between the illuminances, mainly between the EnergyPlus and Daysim/Radiance programmes. These programmes have a maximum difference of 20%, as shown in Fig. 5(a) and (b) and the difference between these programmes and TropLux increases for the afternoon period. This behaviour is repeated for the room with the proportion of 2:1, with the window in the largest façade, as seen in Fig. 4(b).

The room with the proportion of 1:2, whose results are shown in Fig. 4(c), has the lowest illumination values. For this model, there is a greater difference between the illuminances found for the reference points in each simulation programme, the greatest differences being for the second reference point (point B – Fig. 2), further from the window. However, this did not occur on comparing Daysim/Radiance and TropLux, since both programmes used the ray tracing method to calculate the illuminance. As shown in Fig. 5(c), the illuminances found in this model using the EnergyPlus for the point furthest from the window are 50% higher than those obtained using the other two programmes.

On comparing the three geometries it can be noted that the difference between the illuminances increases with the distance of the point analysed from the window. It can also be observed that the room with the proportion of 1:1 has the closest results between the three programmes, while for the room with the proportion of 1:2 EnergyPlus gives high illuminance values for the point furthest from the window.

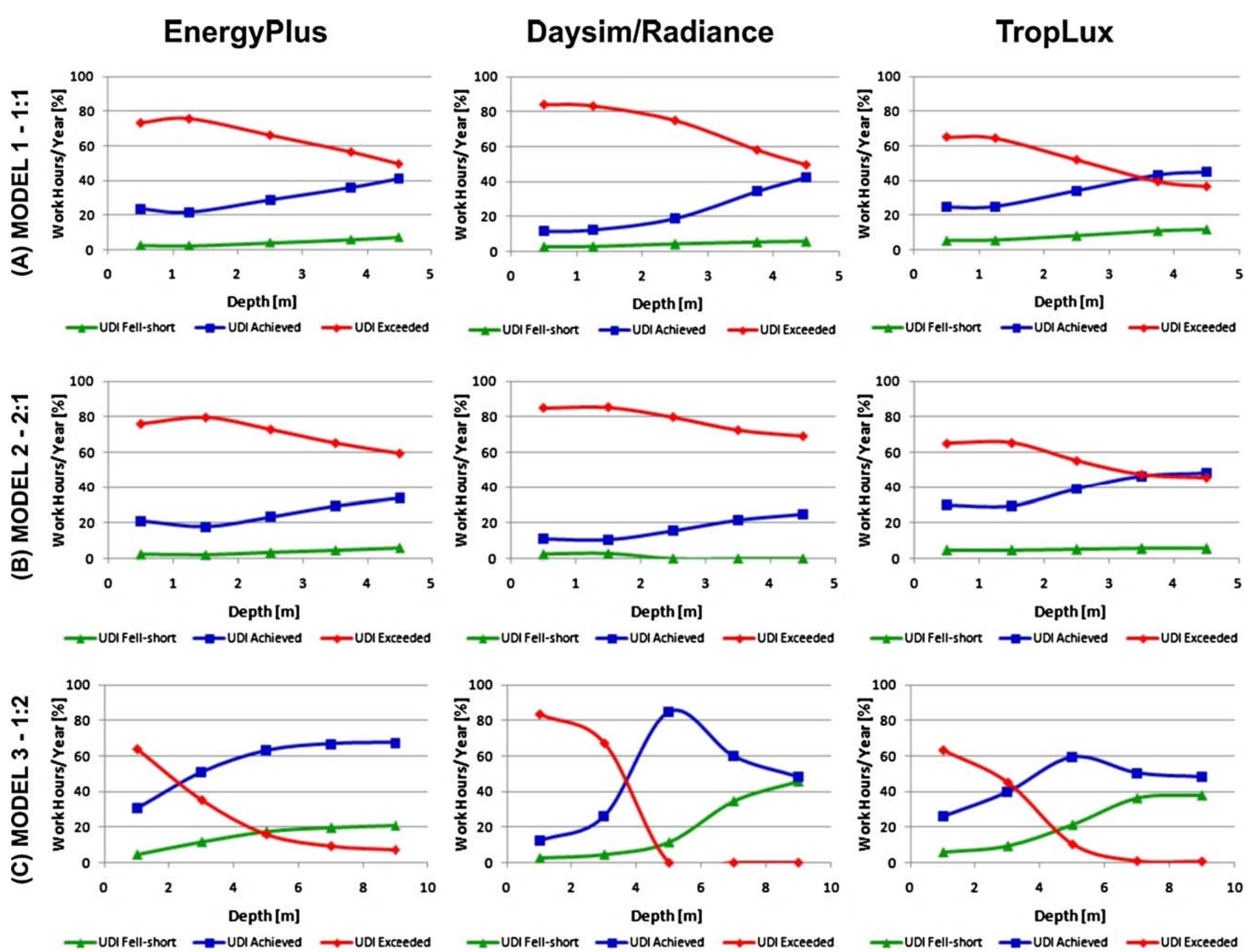

Fig. 6. UDI as a function of distance from the window for the programmes EnergyPlus, Daysim/Radiance and TropLux.

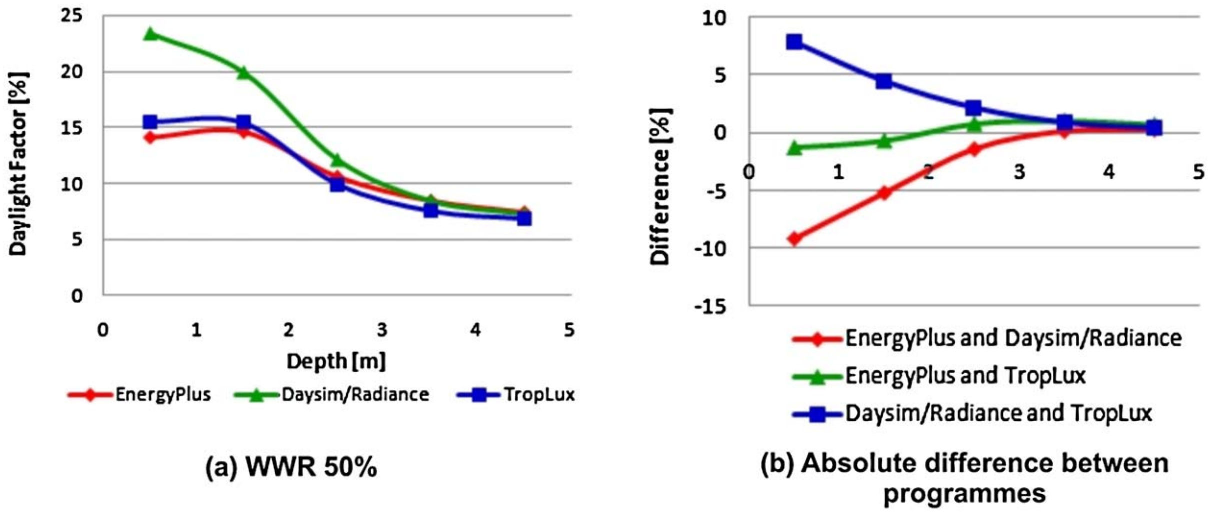

Fig. 7. Daylight factor (DF) for the room with a proportion of 1:1 and WWR of 50%, for Florianópolis.

There follows an analysis based on the verification of the frequency with which each range of illuminances occurs across the room, for the period of 1 year, between 08:00 and 18:00. Fig. 6 shows the frequency distribution of each illuminance range, according to the predetermined ranges given above for the programmes EnergyPlus, Daysim/Radiance and TropLux. For the models with the proportions of 1:1 and 2:1, shown in Fig. 6(a) and (b), there was a high incidence of illuminances above 2000 lx, where for the EnergyPlus and Daysim/Radiance programmes there is an occurrence for over 50% of the time analysed. It can also be noted that the greatest difference between the three programmes is for the part of the room furthest from the window. In this part the three programmes show an increase in the UDI Achieved range of illuminances. However, for the TropLux this range of illuminances becomes the one of greatest occurrence in the room.

For the models with a proportion of 1:2 (Fig. 6(c)) the difference in the resulting distribution of the illuminances of the programmes which use different calculation methods is apparent. It can be observed that, although the Daysim/Radiance programme gives higher illuminances than the TropLux programme, these two programmes have the same distribution across the room. The opposite occurs with the EnergyPlus programme, which distributes the illuminances in a different way across the room.

It can be seen in Fig. 6 that the EnergyPlus and Daysim/Radiance programmes, which use the same sky model, have a greater occurrence of the higher illuminance ranges when compared with the TropLux programme. The calculation of illuminances in the TropLux programme is based on the external illuminances measured in Florianópolis, in 2005.

As mentioned above, the EnergyPlus programme carries out the calculation of internal illuminance through the external illuminance and the daylight factor (DF). Thus, this index was verified for the three room geometries, according to the models shown in Fig. 3.

Fig. 7 was obtained through the simulations for the model with the proportion of 1:1, with a WWR of 50%, and shows a similar behaviour for the DF of the different programmes. In Fig. 7(a) the Daysim/Radiance programme has a maximum DF next to the place where the light enters, while the other two programmes have a maximum DF at 1.5 m from the window. Fig. 7(b) shows the absolute difference found between these models, where it can be observed that the greater the distance between the points analysed

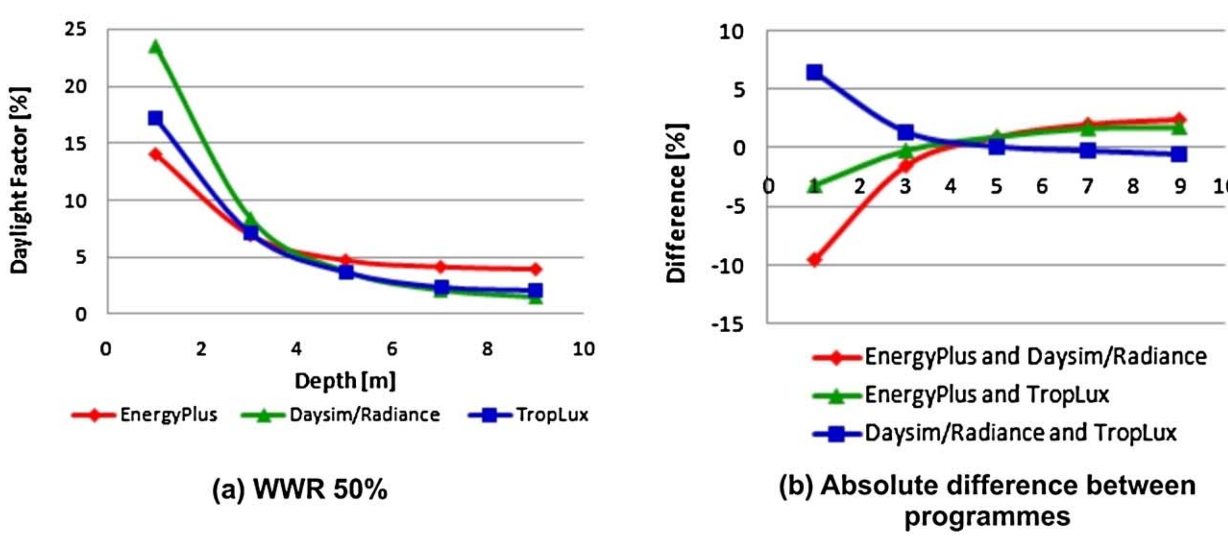

Fig. 8. Daylight factor (DF) for the room with a proportion of 1:2 and WWR 50%, for Florianópolis.

and the window, the less the difference between the DF results. From Fig. 7 it can be noted that the DF obtained for the EnergyPlus and TropLux programmes are similar, which does not occur in the case of the illuminances, as seen in Figs. 4 and 6. The fact that the results of these programmes are similar for the DF but different for the illuminances indicates a difference in the illuminances considered for the calculations (since the EnergyPlus programme uses the DF and the external illuminances to determine the internal illuminance). This also shows that this index may not be the most appropriate for the validation of the daylight simulation, since the internal illuminances are dependent on other variables.

The results obtained for the model with the proportion of 2:1 (10 m × 5 m × 3 m) show that the behaviour of the DF distribution is the same as that for the previous model.

The model with the proportion of 1:2 (5 m × 10 m × 3 m), represented in Fig. 8, has lower DF values. For this model the DF obtained with the EnergyPlus programme remains almost constant after a distance of 6 m, showing the low sensitivity of the programme in simulating the illumination of places further from the point at which the light enters the environment. Through these images it can also be verified that close to the window the highest DF value is that given by Daysim/Radiance and the lowest that by EnergyPlus. At the point furthest from the window the opposite occurs, the highest DF being for EnergyPlus and the lowest for Daysim/Radiance and TropLux.

Fig. 8(b) shows the differences between the results obtained with the programmes for this model, where it can be observed that there is a considerable difference between the programmes for practically all points across the room. The greatest difference is between EnergyPlus and Daysim/Radiance, that is, 10% for the DF at the point closest to the window.

According to Winkelmann and Selkowitz [7], rooms with shapes which are approximately cubic give better results for the split-flux method, used by the EnergyPlus programme to solve the internal reflection. The analyses described herein show that the models which deviate from a cubic shape lead to a greater difference between the results of the programmes.

Through the model with a proportion of 1:2, it was found that as the importance of the internally reflected portion increases, for instance, at the back of the room where there is a lower occurrence

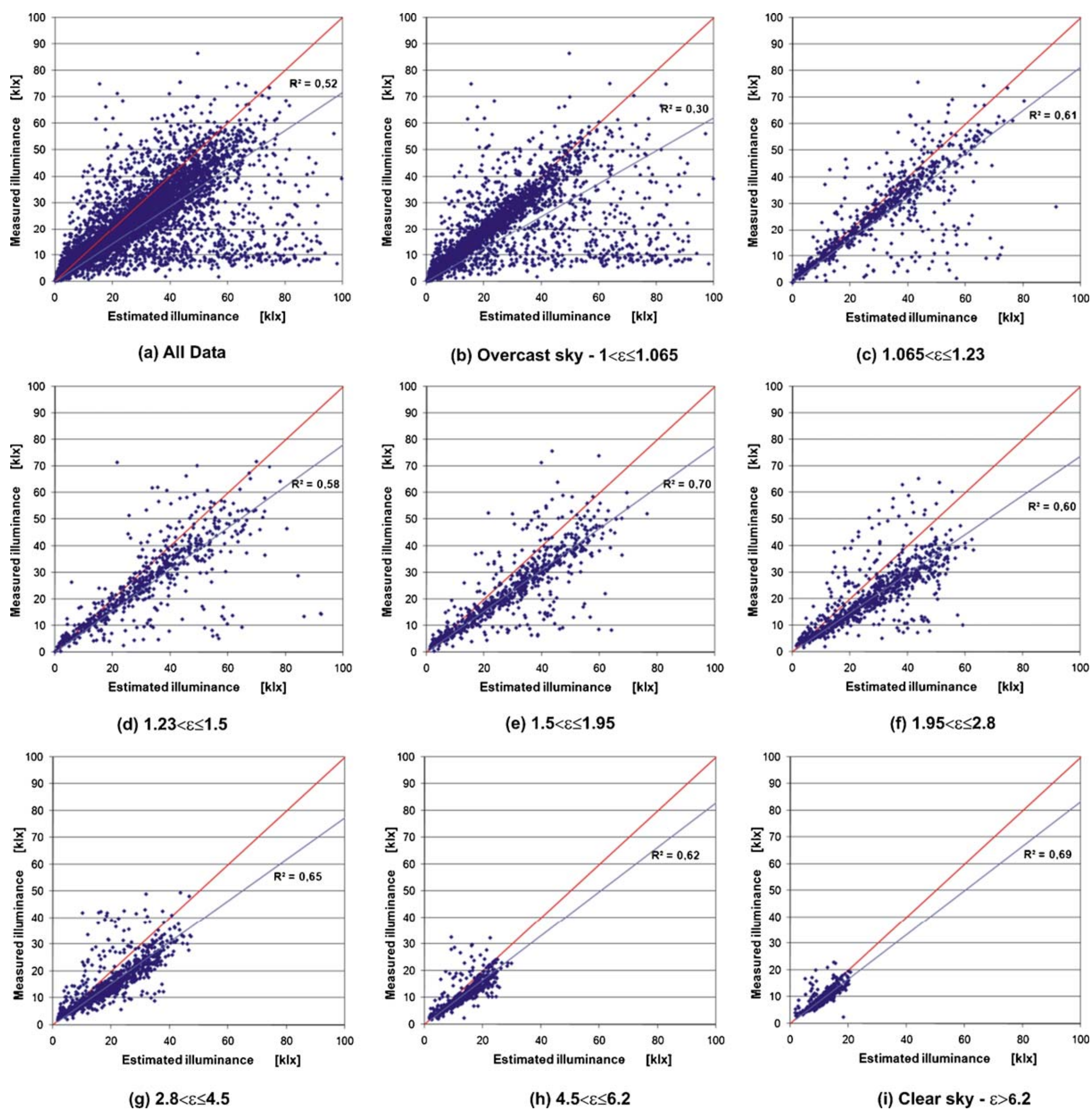

Fig. 9. Correlation between measured illuminances and those calculated through the data collected in Florianópolis between 2003 and 2005.

of direct illuminance, the difference between the results of EnergyPlus and the other two programmes increases, while that between Daysim/Radiance and TropLux decreases. One possible reason for this increase in the difference lies in the methods used to solve the internal reflection, since the first programme uses the split-flux method and the other two the ray tracing method. In the split-flux method the reflected portion is divided equally across the space and thus some points receive a greater portion than actually occurs. Therefore, it is clear that the split-flux method, when used to solve internal reflection, overestimates the illuminances, mainly at points where this portion of light is more influent.

5.2. Considerations related to the analysis of the internal illuminances

The analysis which evaluates the daylight distribution using the UDI, carried out for a period of 1 year, clearly revealed that the calculation method of each programme influences the result for the distribution of light in the environment. In this analysis it can be observed that, from the simulations carried out in TropLux, the illuminances obtained were between 500 and 2000 lx for more than 50% of the period analysed, next to the window, and 30% at the point most distant from the window. For the other programmes this range of illuminances occurred for more than 50% of the period analysed, for the whole room.

The daylight factor (DF) shows the fragility of the EnergyPlus programme in calculating the illuminances for the points furthest from the window. For the deep room model (5 m × 10 m) the results of this programme gave a constant DF value from the middle to the back of the room. The Daysim/Radiance and TropLux programmes gave a DF of 1.8% for the point 9 m from the window, while for the EnergyPlus this value was 3.9%, the same as the value for the middle of the room.

5.3. Evaluation of the external illuminance calculation

For this evaluation the external horizontal illuminances were compared with those calculated using the method developed by Perez et al. [6] and used by the EnergyPlus programme in the calculation of the external illuminances. In this evaluation the measured data for Florianópolis between 2003 and 2005 were used.

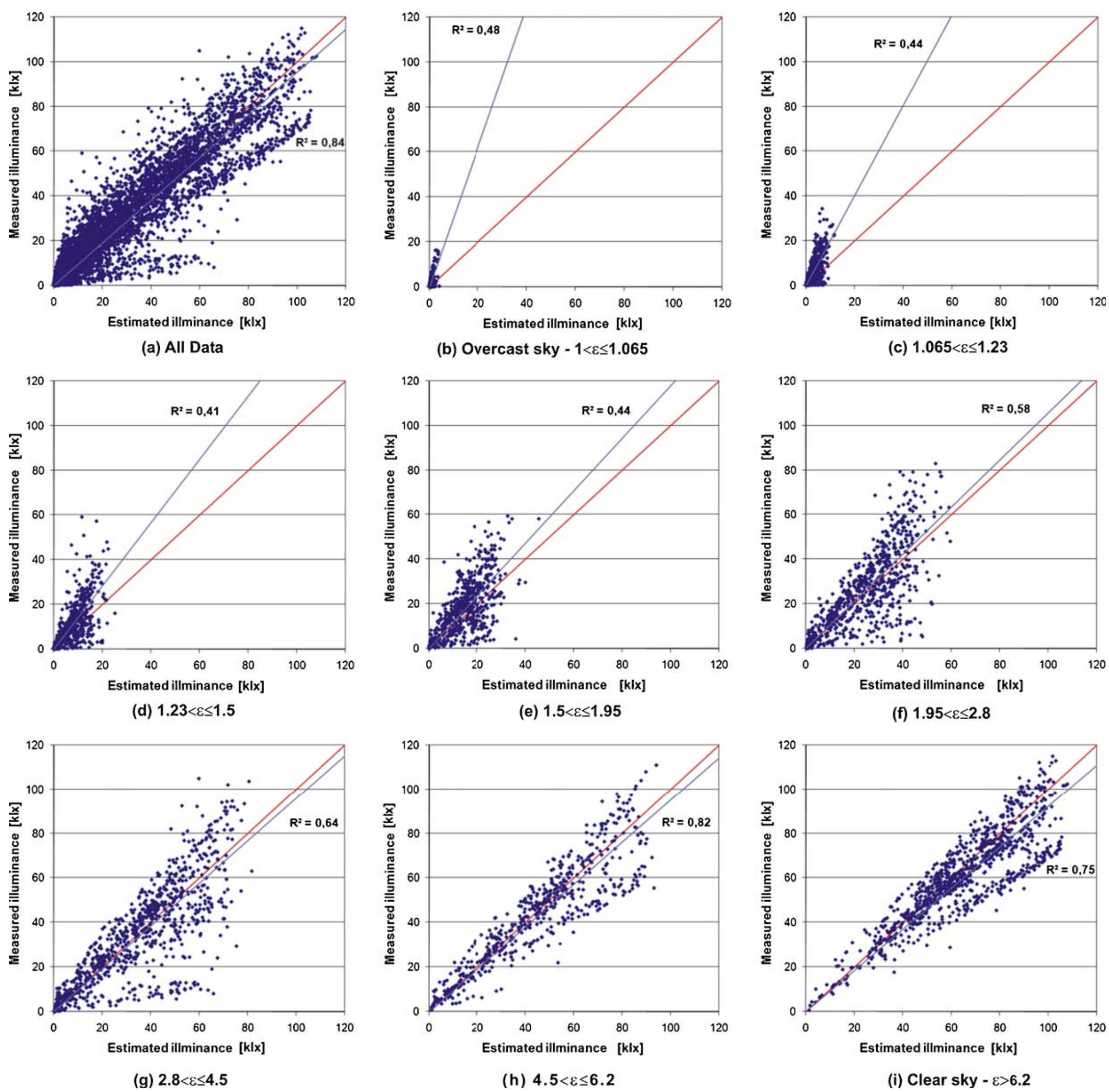

Fig. 10. Correlation between measured direct illuminances and those calculated using the data collected in Florianópolis between 2003 and 2005.

5.3.1. Diffuse external illuminance

The model in question separates the sky types into eight classes and for each one the equation for the calculation of illuminance uses different coefficients. The results given in Fig. 9 show the data for all of the sky classifications, according to Perez et al. [6].

The correlation between the measured and calculated illuminance is demonstrated in Fig. 9, where a high dispersion of the points can be noted, mainly in the graphs which represent the more overcast sky classes. Fig. 9(a) shows the correlation with the data for 2003–2005, for all types of sky, where is it clear that the results obtained using the model of Perez et al. [6] are higher for all measured illuminances, since the linear regression does not coincide with the 45° line and approaches the axis related to the calculated illuminances.

For a better analysis, the results were separated according to the classification of Perez. In Fig. 9(b), the data for an overcast sky are given ($1 < \varepsilon \leq 1.065$) and in Fig. 9(i), the data for a clear sky ($\varepsilon > 6.2$). In these graphs it can be observed that for the overcast sky conditions the dispersion of the points is greater than that observed in the other graphs and the slope of the linear regression differs considerably from the ideal (45°). In Fig. 9(b) and (c) the illuminances for the overcast sky are correlated. In these graphs a greater dispersion of the points is found, mainly for Fig. 9(b) where there is the greatest cloud of points, showing a low correlation between the two sets of values in this sky class.

Table 2 shows the mean bias deviation (MBD) and the root mean square deviation (RMSD) between the measured and calculated illuminances. From the data in Table 2 it can be verified that the model of Perez et al. [6] overestimates the diffuse illuminance for all of the sky classes. The greatest MBD occurs for overcast sky, followed by intermediate sky. As shown in Fig. 9, the largest RMSD value occurs for the portions of overcast sky, with an error above 100%, while the clear sky gave the best response of the model, but far from ideal, with an error of 34%.

5.3.2. Evaluation of direct external illuminance calculation

Based on the same set of data the average direct illuminances were compared with those calculated using the model under study. The results are given in Fig. 10, according to the sky classes.

Fig. 10(a) shows the correlation between the measured illuminances and those calculated from the data of 2003–2005, from which it can be observed that there are two clouds of points. In the first, the calculated values are higher than the measured values, while in the second most of the points lie close to the ideal correlation. The following graphs show the illuminances separated by sky class. Fig. 10(b), (c) and (d) have the largest differences between the data and the estimated illuminances are lower than those measured.

Starting from the intermediate sky, with $\varepsilon > 1.95$, the correlation between the illuminances begins to improve and the linear regression becomes closer to the ideal correlation. Of these sky classes, Fig. 10(h) and (i), which represent clear sky conditions, have the lowest dispersion of the points, and consequently the lowest error.

The values for the mean bias deviation (MBD) and the root mean square deviation (RMSD) between the measured and calculated illuminances are reported in Table 3. It can be verified that the model of Perez et al. [6] tends to overestimate the illuminances for overcast sky, with $\varepsilon < 1.065$, as demonstrated in Fig. 10(b). Table 3 shows that the lowest RMSD found for direct illuminance is 20.58%, for sky class 8, shown in Fig. 10(i). However, the RMSD is greater than 100% for sky classes 1–6.

Table 2
Mean measured diffuse illuminance and statistical evaluation of the Perez model for each sky class, from data for Florianópolis (2003–2005).

ε^a	Mean measured illuminance [klx]	MBD [%]	RMSD [%]
All	17.52	35.49	120.75
1	16.14	39.76	148.10
2	26.03	34.50	128.60
3	25.95	38.55	114.62
4	23.31	35.60	78.98
5	20.72	37.96	72.97
6	15.14	29.61	49.78
7	11.18	22.22	39.99
8	9.20	21.24	34.07

[a] Classification according to Table 1.

Table 3
Average real direct illuminance and statistical evaluation of the Perez model, for each sky class, obtained from data collected in Florianópolis from 2003 to 2005.

ε^a	Average measured illuminance [klx]	MBD [%]	RMSD [%]
All	26.04	62.83	306.88
1	10.60	−38.70	161.51
2	11.89	9.78	219.97
3	14.54	21.36	206.77
4	19.90	12.48	123.66
5	28.15	23.19	131.67
6	34.67	31.09	129.77
7	41.21	4.42	34.00
8	56.69	7.31	20.58

[a] Classification according to Table 1.

6. Conclusions

Applying the methodology described herein, the simulations were carried out using the EnergyPlus, Daysim/Radiance and TropLux programmes. The Daysim/Radiance and TropLux programmes use similar methods of calculation; however, they are based on different sky models. The EnergyPlus and Daysim/Radiance models have different methods of calculation, but they are based on the same sky model.

The first analysis carried out compared the programmes in terms of the distribution of daylight in three rooms, using the Useful Daylight Illuminances (UDI). It was observed from the simulations carried out with EnergyPlus and with Daysim/Radiance that the illuminances obtained are most frequently in the range of excessive illuminances while for the TropLux the values occur in the range of illuminances for replacement of artificial light with daylight, at the back of the room. This shows that the difference observed in the internal illuminances, calculated by the three programmes, may be due to the sky model used, and not only the calculation method, since the programmes which use the same sky model have similar illuminance values.

Through the analysis of the daylight factor (DF), it was concluded that the difference in the illuminances found is due both to the sky model and to the difficulty which the EnergyPlus encounters in solving the internal reflectance. On comparing the DF next to the window similar values are obtained for the EnergyPlus and TropLux programmes, but the illuminances differ. Given that the EnergyPlus programme solves the internal illuminance through the calculation of the DF and the external illuminances, the external illuminance must be one of the reasons for the high illuminances obtained by EnergyPlus. For deep rooms, the EnergyPlus programme gives a constant DF from the middle to the back of the room, which highlights a deficiency of this programme in solving the internal reflectance, since for these points the illuminance is the result, mainly, of the portion of light reflected in the environment.

For the evaluation of external illuminances calculated through the method developed by Perez et al. [6] and used by the EnergyPlus programme, the illuminances measured in Florianópolis were compared with those calculated using this method from parameters collected together with the illuminances. In these comparisons it can be observed that the calculated illuminances are overestimated and that the clearer the sky the better the correlation between the calculated and measured illuminances. That is, for both the diffuse and the direct illuminances, the greatest errors occur for conditions of overcast sky. In summary, the comparison between the measured and calculated external illuminances showed that the EnergyPlus programme, through the model of Perez et al. [6], does not reproduce adequately the daylight conditions observed in Florianópolis. This indicates the need to search for models to predict illuminances which respond in a form appropriate for the sky conditions found in the region studied. Given that this model is used in the EnergyPlus programme to calculate the daylight, the model used to calculate the external illuminance is another factor which leads to the overestimated calculation of illuminances in the environments analysed.

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